

Finding heavy Higgs bosons heavier than $2m_W$ in dileptonic W -boson decays

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(Dated: May 7, 2012)

We reconsider observables for discovering a heavy Higgs boson (with $m_h > 2m_W$) via its dileptonic decays $h \rightarrow WW \rightarrow l\nu l\nu$. We show that observables generalizing the transverse mass that take into account the fact that both of the intermediate W bosons are likely to be on-shell give a significant improvement over the variables used in existing searches. We also comment on the application of these observables to other decays which proceed via narrow-width intermediates.

The LHC collaborations have now excluded a heavy Higgs boson, with mass between 127 and 600 GeV [1, 2], at the 95% confidence level, assuming that its production and decay proceed according to the predictions of the Standard Model. Nevertheless, there is a clear motivation to continue the search in this mass region. Indeed, theories beyond the Standard Model, with additional degrees of freedom, typically predict a lower cross section times branching ratio for Higgs production and decay in any given channel, for three reasons. Firstly, the branching ratio will necessarily be reduced whenever there are extra states into which a given Higgs boson may decay. Secondly, in theories with an extended scalar sector, mixing reduces the cross section to produce a given mass eigenstate. Thirdly, since the dominant production mechanism for Higgs bosons at the LHC is via loop-level gluon fusion, the production cross section will be changed by the presence of additional coloured states in the theory. If one of these states plays the rôle of cancelling the quadratic divergence in the Higgs mass, coming from a loop of top quarks, then it necessarily interferes destructively with the dominant contribution to gluon fusion in the Standard Model, which also comes from a top quark loop [3]. Furthermore, it is observed (though sadly no theorem to the effect has been proven) that the cross-section is reduced in all models in which the Higgs boson is composite [3–7].

One way to search for a heavy Higgs boson is to look for evidence of it decaying to the fully leptonic final state $l\nu l\nu$ (where l is an electron or muon) which results from an intermediate pair of (possibly virtual) W -bosons [8–10]. A key step in many such analyses comprises a selection, or cut, based on a variable that should have a strong correlation with the mass of the Higgs boson in ‘signal’ events. Typically this variable will be a transverse mass of some kind, of which many have been described in the literature [11, 12]. The transverse mass variable m_T of Ref. [13] (see also [8, 14]) is used in current LHC $h \rightarrow WW \rightarrow l\nu l\nu$ searches.¹

It has previously been observed [15] that a kinematic variable m_T^{bound} (which, for reasons that will become clear, we refer to henceforth as m_T^{lower}) which demands intermediate mass-shell constraints for the tau leptons might prove advantageous in $h \rightarrow \tau\tau$ decays. As was indicated in that paper, the same variable (after the trivial replacement $m_\tau \rightarrow m_W$) might also prove useful in the context of $h \rightarrow WW$ when a heavy Higgs boson has mass greater than $2m_W$, since the intermediate W -bosons should be produced close to their mass shells. Substantiation of this suggestion was left open to further study and one of our intentions here is to perform that follow-up. We also intend to go somewhat further, in providing a complete discussion of the variables that characterize the kinematics of $h \rightarrow WW \rightarrow l\nu l\nu$ decays, in a sense that will be made explicit below. We will find that the pre-existing variables m_T or m_T^* [16] provide a complete description in cases where neither or either, respectively, of the intermediate W -bosons is produced on-shell.² A complete description of the cases when both of the W -bosons are produced on-shell requires not only the extant variables m_T^{lower} and m_{T2} [18, 19], but also a new variable, which we denote m_T^{upper} . Our simulations suggest, moreover, that m_T^{upper} gives a significant improvement in discovery potential for $h \rightarrow WW \rightarrow l\nu l\nu$.

Having finished our preamble, we now describe more explicitly how variables of this kind may provide a complete characterization of the kinematics of events. Since the decay of the parent Higgs boson involves invisible neutrinos, one cannot find a variable that measures its mass directly; rather the best one can do is to find variables that bound the mass of the parent in some way. Myriad variables of this type may exist and what one would like to do, presumably, is to find the variable or variables that give the *optimal* bounds on the mass in an

the time; we now refer to it simply as m_T , in line with both the ATLAS and CMS collaborations.

² In the mass range $m_W < m_h < 2m_W$, one might reasonably assume that one or other of the W bosons is produced on shell [17]. However, simulations reported in [16] found no significant improvement in discovery potential when m_T^* was substituted for m_T in existing ATLAS collaboration searches.

¹ The variable m_T was referred to as m_T^{true} in [13] to distinguish it from other, approximate transverse mass variables in use at

event.

This search for the optimal variables can be done in a more-or-less definitive way if one is willing to restrict one's attention to kinematics alone. That is to say, suppose one assumes that a signal event corresponds to some decay topology (here the decay of a parent Higgs into two intermediate W resonances, followed by decays of each intermediate into a combination of visible and invisible daughter particles). One may then write down the various kinematic constraints (corresponding to energy-momentum conservation and the mass-shell conditions) and ask which values of the *a priori* unknown masses are allowed, in the sense that the kinematic constraints then admit solutions in which the unmeasured momenta and energies in the event are real and real-positive, respectively. The resulting allowed mass region is an event observable and encodes all of the information which can be gleaned about the masses in an event using kinematics alone. The boundary of the allowed region can be described in terms of one or more relations between the masses, which are themselves event observables and which give the optimal bounds on the mass in an event. Given multiple events, the allowed mass region is obtained as the intersection of the allowed regions for each event and is itself an observable.³

This abstract recipe leads, in many cases, to simple, pre-existing observables. In the canonical example of a decay of a parent to a single invisible daughter (together with possibly multiple visible particles), the observable that results [23] is the familiar transverse mass, m_T [24], invoked in the discovery of the W -boson [25] in its decay to a charged lepton and a neutrino; for single parent decays into multiple invisibles, the resulting variable [13] is m_T ; for identical decays of a pair of parents into invisible particles, the variable [23, 26, 27] is m_{T2} .

Thus, these variables encode all of the information that is available from kinematic considerations alone (subject to an assumed decay topology) and there is no point in trying to devise further variables to glean further information from kinematics.⁴

In the next Section, we firstly try to prove the equivalence between the kinematic constraints with one intermediate on-shell and the variable m_T^* and secondly the

equivalence between the constraints with both intermediates on-shell and the variables m_T^{lower} and m_{T2} . Our first attempt at a proof succeeds: m_T^* is equivalent to all of the information contained in the kinematic constraints when one intermediate is on-shell. But for the topology with both intermediates on shell, we fail. Indeed, we show that m_T^{lower} and m_{T2} do not capture all of the information in the kinematic constraints. Rather there is a third, distinct variable, which we call m_T^{upper} , and which gives an *upper* bound on the mass of the Higgs (or whatever parent particle is being considered).

In what follows we show that while m_T^{lower} only marginally enhances the discovery potential for a Higgs boson using current ATLAS collaboration search strategies, m_T^{upper} gives a significant improvement. In an Appendix, we discuss issues related to the existence of m_T^{lower} and m_T^{upper} .

KINEMATIC EQUIVALENCE

Since we are concerned with the three transverse masses m_T , m_T^* and m_T^{lower} , it is helpful to recall and compare their definitions. All three make the assumption that the observed $l\nu l\nu$ final state resulted from the decay of a single progenitor particle or resonance (i.e. the Higgs in the case of the signal) whose mass is, *a priori*, unknown. All three assert that the sum of the transverse momenta of the neutrinos should equal the observed missing transverse momentum. All three accept that: (i) the way the transverse momentum is shared between the two neutrinos is unknown, and (ii) that the longitudinal momentum component of each neutrino is unknown. Finally, all three transverse masses are defined to be *the greatest possible lower bound for the unknown mass of that progenitor particle*, subject to consistency and any remaining constraints.⁵ It is only in these remaining constraints that the transverse masses differ: m_T applies none, m_T^* permits only neutrino momenta that place *at least one* W -boson on mass-shell, while m_T^{lower} allows only neutrino momenta that place *both* W -bosons on mass-shell. In short, history would have been kinder to us had m_T , m_T^* and m_T^{lower} been named $m_T^{W^*W^*}$, $m_T^{WW^*}$, and m_T^{WW} respectively. The variables and constraints are summarized in Table I.

We now attempt to prove the equivalence between the

³ Whether this observable is the optimal observable for discovering the parent is unclear. To settle this, one would first have to define what one meant by an optimal discovery observable. For discussion, see *e.g.* [20–22].

⁴ The equivalence between variables and kinematics is also important for the purposes of determining which particle masses can be measured using kinematics alone: as an example, for a (possibly pair-produced) parent particle that decays off-shell to multiple invisible particles, it is a theorem that one can – at least in principle – measure the parent mass and the sum of the masses of the invisible daughter particles using kinematic information alone [28–31].

⁵ Equivalently, they may be defined to be the smallest possible progenitor mass obtainable by a search over all unknown neutrino momentum components that satisfy the remaining constraints. Indeed, this brute force search technique is used in the authors' implementations of m_T^* and m_T^{lower} calculators. These C++ implementations, free of external dependencies, are available on request. A simple analytic answer is available for m_T – see Eq. (1) of [16].

Name	Ref.	Bounding	Constraints
m_T	[8, 13, 14]	$H^\mu H_\mu$	(1) to (3)
m_T^*	[16]	$H^\mu H_\mu$	(1) to (3) and either (4) or (5)
m_T^{lower}	[15]	$H^\mu H_\mu$	(1) to (5)

(a) Variables

$$\begin{aligned}
p_\nu^\mu p_{\nu\mu} &= p_l^\mu p_{l\mu} = 0, & (1) \\
p_\nu'^\mu p_{\nu\mu}' &= p_l'^\mu p_{l\mu}' = 0, & (2) \\
p_{\nu T} + p_{l T} &= \not p_T, & (3) \\
(p_\nu^\mu + p_l^\mu)(p_{\nu\mu} + p_{l\mu}) &= m_W^2, & (4) \\
(p_\nu'^\mu + p_l'^\mu)(p_{\nu\mu}' + p_{l\mu}') &= m_W^2. & (5)
\end{aligned}$$

(b) Constraints

TABLE I: A comparison of the three mass-bound variables. The final state four-momenta of the two visible leptons are p_l^μ and $p_l'^\mu$ respectively. The hypothesized four-momenta of the two neutrinos are given by the two p_ν^μ . The missing transverse momentum is $\not p_T$. In all three cases, the variable named in (a) is defined to be the maximal lower bound on the invariant $H^\mu H_\mu$, where $H^\mu = p_\nu^\mu + p_l^\mu + p_\nu'^\mu + p_l'^\mu$, subject to the indicated subset of the constraints shown in (b).

variables m_T^* and m_T^{lower} and the corresponding kinematic constraints.

One intermediate on-shell

The theorem to be proved is a formalization of the colloquial: m_T^* is equivalent to all the information contained in the kinematic constraints. To wit, in a notation in which $p^\mu = (E, p_T, q)$:

Theorem 1 *The kinematic constraints (1) to (3) and either (4) or (5) admit a solution with momenta in \mathbb{R} and energies in \mathbb{R}^+ iff.*

$$m_h \geq m_T^*. \quad (6)$$

Here, m_T^* is defined as the minimum value of

$$m_h \geq m_T^* \quad (7)$$

obtained by varying the unobserved momenta in \mathbb{R} and energies in \mathbb{R}^+ . This definition makes the necessity of $m_h \geq m_T^*$ obvious; it is the sufficiency of the condition that requires deliberation.

So, does $m_h \geq m_T^*$ imply that the kinematic constraints have a solution? One way to show this would be to consider every $m_h \geq m_T^*$ and explicitly construct a solution therefor. An easier way is to show that one can find solutions corresponding to arbitrarily large m_h and then to invoke continuity and the intermediate value theorem to show that one can find solutions for any m_h between m_T^* and ∞ .

Let us then exhibit a solution for arbitrarily large m_h that satisfies constraints (1) to (4) (if the other W is on-shell, the required solution can be obtained by interchanging primed and unprimed quantities). It is given by

$$p_\nu'^\mu = \lim_{q_\nu' \rightarrow \infty} (\sqrt{q_\nu'^2 + \not p_T^2}, \not p_T, q_\nu'), \quad (8)$$

$$p_\nu^\mu = (|q_\nu|, 0, q_\nu) \quad (9)$$

where q_ν is given by either of

$$q_\nu = \frac{m_W^2}{2p_{lT}^2} \left(q_l \pm \sqrt{q_l^2 + p_{lT}^2} \right). \quad (10)$$

This yields a value of m_h given by

$$\begin{aligned}
m_h^2 &= \lim_{q_\nu' \rightarrow \infty} (m_W^2 + 2(p_l + p_\nu) \cdot p_l' + 2(p_l' + p_l + p_\nu) \cdot p_\nu') \\
&\rightarrow 2((E_l' + E_l + |q_\nu|)\sqrt{q_\nu'^2 + \not p_T^2} \\
&\quad - (p_{lT}' + p_{lT}) \cdot \not p_T - (q_l' + q_l + q_\nu)q_\nu') \\
&\rightarrow 2((E_l' - q_l') + (E_l - q_l) + (|q_\nu| - q_\nu))q_\nu', \quad (11)
\end{aligned}$$

where in the last line we assumed $q_\nu' > 0$ without loss of generality (this amounts to a choice of which proton beam constitutes the $+z$ direction). The terms in parentheses in the coefficient are each positive semi-definite and so no cancellation of the coefficient of q_ν' can occur. Thus m_h grows without bound unless all terms vanish. To do so, both leptons must have vanishing transverse momenta, in which case they would fall outside the detector acceptance and this would not be identified as a di-lepton plus missing momentum event. ■

Both intermediates on-shell

It is now easy to show that an analogous theorem cannot be proven for m_T^{lower} , which applies to the topology in which both constraints (4) and (5) are satisfied. The reason is that one cannot find solutions to the kinematic constraints corresponding to arbitrarily large m_h . Indeed, one can easily convince oneself that to get arbitrarily large m_h , at least one of the neutrino momenta must become arbitrarily large. But each neutrino is now produced in the decay of a W -boson, which simultaneously results in a charged lepton of finite (and measured) momentum. Now, there is only one way in which a two-body decay can produced one daughter of finite momentum and another with infinite momentum in the lab frame: the rest frame of the W must be infinitely boosted exactly

in the direction of motion of the neutrino (as measured in the W rest frame). This doesn't work, because the lepton momenta are then not only finite but arbitrarily small, in contrast with their measured values in a generic event.

Thus, there is more information in the kinematic constraints than is captured by m_T^{lower} alone. In particular, since m_h cannot reach arbitrarily large values in events, there is a distinct variable, obtained by *maximizing* the sum of lepton and neutrino momenta in events, subject to the above constraints. This variable will be bounded *below* by m_h and we call it m_T^{upper} . By the intermediate value theorem, this variable, together with m_T^{lower} does contain all of the information in kinematics.

MONTE CARLO SIMULATIONS

Simulations, similar to those performed in Ref [13], are used to test the extent to which using m_T^{lower} and m_T^{upper} might be expected to enhance the statistical significance of a $h \rightarrow WW$ signal above the dominant WW continuum background and the $t\bar{t}$ background. We use the HERWIG 6.505 [32, 33] Monte Carlo generator, with LHC beam conditions ($\sqrt{s} = 7$ TeV). Our version of the generator includes the fix to the $h \rightarrow WW^{(*)}$ spin correlations described in [34]. We generate unweighted events for Standard Model Higgs boson production ($gg \rightarrow h$) and for the dominant backgrounds, $q\bar{q} \rightarrow WW$, and $t\bar{t}$ production.⁶ We use the leading order Standard Model cross section for all values of m_h .

The missing transverse momentum is calculated from the negative sum of the p_T of visible particles within the fiducial region $p_T > 0.5$ GeV and $|\eta| < 5$. The detector resolution is simulated by smearing the magnitude of the missing momentum vector with a Gaussian resolution function of width $\sigma_{\cancel{p}_T}/\cancel{p}_T = 0.4 \text{ GeV}^{1/2}/\sqrt{\Sigma}$ where Σ is the sum of the $|\vec{p}_T|$ of all visible fiducial particles.

For each value of m_h , fifty pseudo-experiments are performed, each corresponding to 10 fb^{-1} . Selection cuts are applied, requiring:

- Exactly two leptons $\ell \in \{e, \mu\}$ with $p_T > 15$ GeV and $|\eta| < 2.5$
- Missing transverse momentum, $\cancel{p}_T > 30$ GeV
- $12 \text{ GeV} < m_{\ell\ell} < 300 \text{ GeV}$
- No jet with $p_T > 20$ GeV

⁶ Other backgrounds, such as $Z \rightarrow \tau\tau$, are rendered sub-dominant by the cuts discussed below.

- $Z \rightarrow \tau\tau$ rejection: the event was rejected if $|m_{\tau\tau} - m_Z| < 25 \text{ GeV}$ and $0 < x_i < 1$ for both $i \in \{1, 2\}$ ⁷

For each of the three candidate discriminant variables m_T , m_T^{lower} , and m_T^{upper} , and for each trial value of m_h , a likelihood is calculated for each of two hypotheses \mathcal{H} : a background-only (B) hypothesis and a signal plus background hypothesis ($S + B$). The log likelihood

$$\log \mathcal{L}_{\mathcal{H}} = \left\langle \log \prod_{i \in \mathcal{D}} P(n_i^{(j)} | x_i^{\mathcal{H}}) \right\rangle_{j=1 \dots 50}$$

is calculated from the average over 50 pseudo-experiments. For each pseudo-experiment j the number of events observed in the i th bin is $n_i^{(j)}$. The expected number of events $x_i^{\mathcal{H}}$ for each bin and for each of the two hypotheses \mathcal{H} is calculated from independent Monte Carlo samples containing 10^6 events for each trial value of m_h and 10^7 events for the WW background. The likelihood for each $n_i^{(j)}$ is calculated using a Poisson distribution with mean $x_i^{\mathcal{H}}$. The difference $-2\Delta \log \mathcal{L} = -2(\log \mathcal{L}_{S+B} - \log \mathcal{L}_B)$ quantifies the statistical significance with which we can expect the Higgs boson signal to be observed.

The discovery potential using separately m_T , m_T^{lower} , or m_T^{upper} , is shown in Figure 1. The first result is that when $m_h \approx 2m_W$ the doubly-on-shell lower bound variable, m_T^{lower} has significantly better sensitivity than the simple transverse mass m_T (or indeed the singly-on-shell variable m_T^* , which is almost indistinguishable from m_T [16]). Secondly, we observe that the distribution of the doubly-constrained *upper* bound m_T^{upper} shows a markedly greater discovery potential again, relative to either m_T or m_T^{lower} . Since any event satisfying the constraints of Table I will generate both a lower and an upper bound, and since those bounds are not closely correlated (Figure 2) each adds information relative to the other.

OTHER FINAL STATES

We note that it is also possible to construct equivalent bounds for any other decays of the form $A \rightarrow B+C$ where B and C are produced near their mass shell and each decays to an invisible particle and one or more visible particles. A case relevant to LHC Higgs physics is the decay mode $h \rightarrow \tau\tau$, followed by semi-invisible decay of each of the τ leptons. Previous simulations [15] indicated that adding the tau mass constraints led to improved discrimination of the signal from the dominant $Z \rightarrow \tau\tau$

⁷ The variable x_i is the momentum fraction of the i th tau carried by its daughter lepton and $m_{\tau\tau}$ is the di-tau invariant mass. They are calculated using the approximation that each τ was collinear with its daughter lepton.

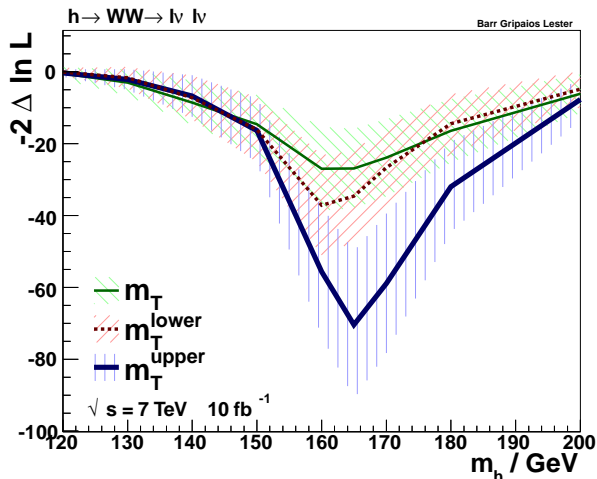


FIG. 1: Higgs boson discovery potential as a function of m_h , for each of three different kinematical variables, m_T , m_T^{lower} , and m_T^{upper} . The centre of each band indicates the difference in log likelihood between models with and without a Higgs boson contribution. Lower values correspond to better discovery potential. The half-width of each band gives the root-mean-squared variation over the 50 pseudo-experiments. The integrated luminosity simulated is 10 fb^{-1} .

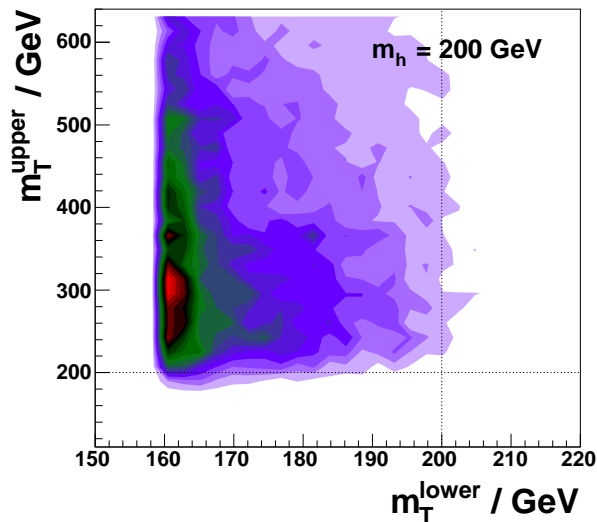


FIG. 2: The distribution of m_T^{upper} vs. m_T^{lower} for a Higgs boson signal sample with $m_h = 200 \text{ GeV}$.

background, using the lower bound m_T^{lower} [15]. However further simulations indicate that there seems to be little additional discrimination available from the upper bound in this case, perhaps because of the large hierarchy in masses between m_h and m_τ .

CONCLUSION

When a heavy higgs boson with mass $> 2m_W$ decays via $h \rightarrow WW \rightarrow \ell\nu\ell\nu$, we have shown that one can use knowledge about the narrow width of the intermediate W bosons to construct both upper and lower bounds on m_h . We demonstrate that these two bounds together make maximal use of the kinematic information about m_h in each event. Since the two bounds are reasonably uncorrelated, the ATLAS and CMS experimental collaborations should be able to obtain improved kinematic sensitivity in an analysis which simultaneously makes use of both bounds.

We note that the same suite of variables can find use for discovery or mass determination in other decays of the form $A \rightarrow B + C$ followed by semi-invisible decay of each narrow-width intermediate particle.

This work was supported by the Science and Technology Facilities Council of the United Kingdom, by the Royal Society, by the Institute for Particle Physics Phenomenology, by Merton College, Oxford, and by Peterhouse, Cambridge. We gratefully acknowledge T.J. Khoo for helpful comments.

Appendix: Remarks on the existence of m_T^{lower} and m_T^{upper}

Note that there exist ‘input momenta’ for which it is not possible to satisfy all the constraints required by m_T^{lower} (and m_T^{upper} , to which the following arguments equally apply). For events containing such momenta, a value of m_T^{lower} cannot be computed. In effect, the variable does not exist as those events are incompatible with the assumptions at face value.⁸ It is known [15] that m_T^{lower} exists if and only if m_{T2} [18, 19] for the dilepton system is less than m_W . This condition may easily be violated if one or both W -bosons is off mass-shell, confirming that there is little sense in applying m_T^{lower} to events with $m_h < 2m_W$. The criterion $m_{T2} < m_W$ can also be violated in $m_h > 2m_W$ events with sufficiently large detector mis-measurements, even if both W -bosons are produced on-shell. The largest source of mis-measurement is the missing transverse momentum, whose distribution can have a large, non-Gaussian tail. Though not discussed in [15], this potential problem might be thought more worrisome in the case of $h \rightarrow \tau\tau$ decays, since the typical size of an LHC \cancel{p}_T mismeasurement greatly exceeds m_τ . It is thus hard to see, naïvely, how the condition $m_{T2} < m_\tau$ may be maintained. Nonetheless, one is assisted by a

⁸ Note also that the variables m_T and m_T^* exist for all input momenta, and are therefore usable even when m_T^{lower} is not. See discussion in [15].

property of the m_{T2} variable under which large mis-measurements of \not{p}_T can lead, in a non-negligible number of events, to small changes (relative to m_τ) in the value of m_{T2} , provided that the intermediate particles in the production process are sufficiently light. Indeed, in the limit that the intermediate pair of particles are massless, their decay products are collinear and so the true \not{p}_T vector lies in the smaller of the two sectors bounded by the two visible transverse momenta. It follows that for such configurations m_{T2} must vanish, as there exists a splitting of the \not{p}_T (in fact the ‘true’ splitting) for which the transverse mass of each pair of decays is zero. That m_{T2} is ‘small’ for well-measured events in this limit is not surprising – after all, m_{T2} is supposed to be bounded above by the mass of either member of the pair, and we are taking the limit in which those masses go to zero. What is surprising, if anything, is that m_{T2} can be forced *exactly* to zero in a large number of events, even for finite yet small intermediate particle masses. In this sense we can say that m_{T2} goes to zero faster than m_τ . It follows that for such signal events, any mis-measurement of \not{p}_T (even large ones) that keeps it ‘between’ the visible particles’ transverse momenta, leads to no observable change in m_{T2} . Moving away from the above limit, such that the intermediate particles now have non-zero but still small intermediate masses, we see that changes in m_{T2} can still be small, even for large mis-measurements of \not{p}_T , provided that mis-measured \not{p}_T remains in the appropriate region of the transverse plane.

This goes some way towards explaining why it was found in [15] that m_T^{lower} could remain well-defined for a large number of $h \rightarrow \tau\tau$ events, even in the presence of momentum mis-measurements. For $h \rightarrow WW$ events this issue is much less of a concern; we find that m_T^{lower} exists for all but a few *per cent* of the $h \rightarrow WW$ signal events we simulate. We attribute the greater frequency with which m_T^{lower} exists to the greater ease with which the momentum mis-measurement errors (which have a natural scale far below m_W) may be incorporated into the intermediate particle mass constraints (whose natural scale is m_W).

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